Super-Resolution Microscopy by Microspheres Embedded in Movable Slabs

Vasily N. Astratov (astratov@uncc.edu), **Kenneth W. Allen, and Yangcheng Li**

University of North Carolina at Charlotte, U.S.A.

Nicholaos I. Limberopoulos, Dennis E. Walker Jr., and Augustine M. Urbas

Air Force Research Laboratory, U.S.A.

Vladimir Liberman

Lincoln Laboratory, Massachusetts Institute of Technology, U.S.A.

Recent years have witnessed a breakthrough in achieving truly nanoscale resolution by a fluorescent super-resolution microscopy. The label-free microscopy develops more slowly than fluorescent microscopy for two reasons. First, the mechanisms of label-free imaging rely on much more subtle light-scattering processes in nanoplasmonic or biomedical objects that result in lower effective contrast of images. Second, good “point”-sources in a form of dye-molecules, fluorophores or quantum dots are not readily available in a label-free microscopy that complicates the experimental quantification of resolution.

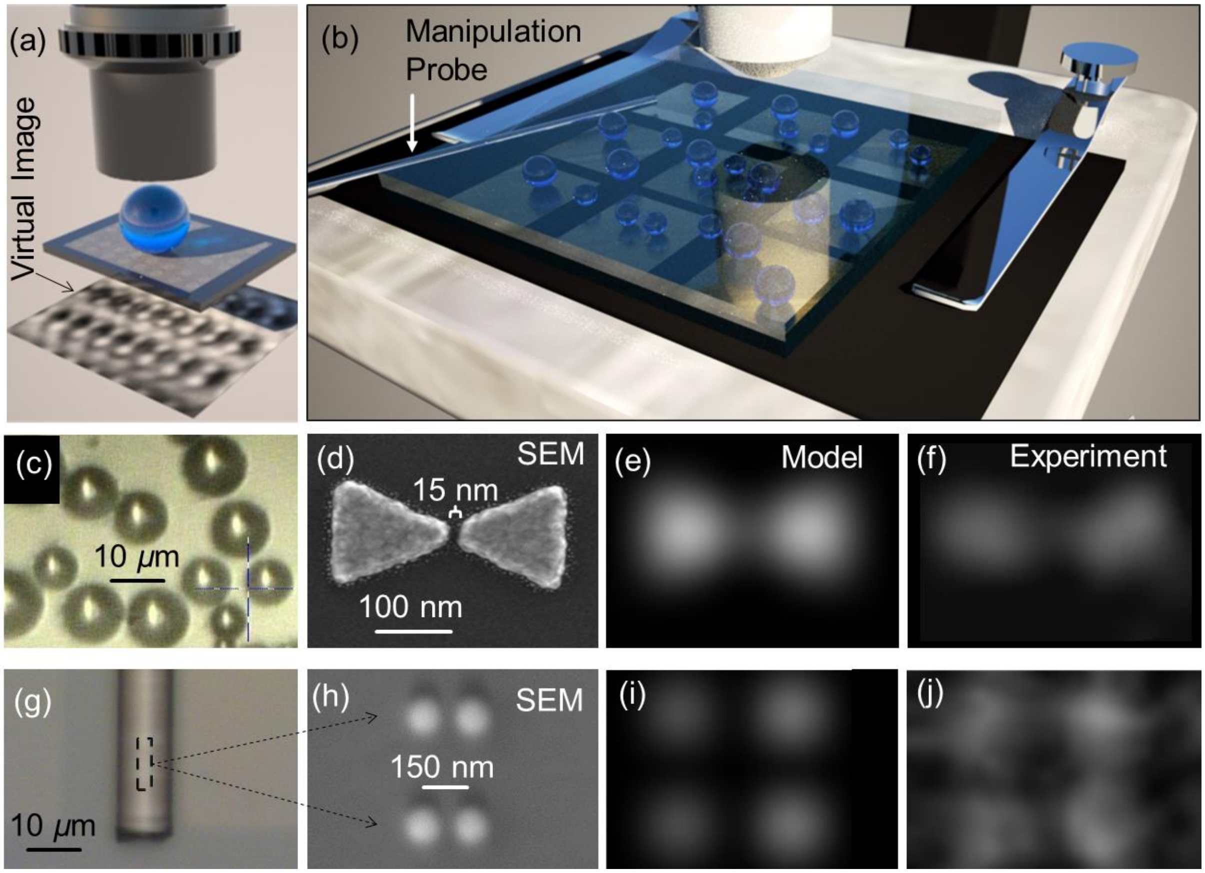
Super-resolution microscopy by microspheres emerged as an extraordinary simple and efficient method of label-free imaging.[1] This method was further advanced by a proposal of using high-index (n~2) microspheres embedded in elastomeric slabs.[2] The fundamental question about why the resolution of this method can exceed the Abbe limit is debated in the literature. The possible mechanisms include resonant enhancement of the optical near-fields and formation of “photonic nanojets” by mesoscale microspheres, as well as excitation of localized surface

Distribution A: Public Release

The Lincoln Laboratory portion of this work was sponsored by the Department of the Air Force under Air Force Contract FA8721-05-C-0002. Opinions, interpretations, recommendations and conclusions are those of the authors and are not necessarily endorsed by the United States Government.

plasmon resonances and plasmon-polariton waves in nanostructured objects. The resolution values have been determined by using subjective criteria that resulted in a broad range of resolution claims from $\lambda/6$ to $\lambda/17$, where λ is the illumination wavelength.

In this work, we fabricated PDMS slabs with embedded high-index ($n \sim 2$) barium titanate glass microspheres and showed for the first time that these slabs provide the optical super-resolution imaging combined with the surface scanning capability.[3,4] We also developed a novel approach to treatment of super-resolved images in label-free microscopy based on using point-spread functions (PSFs) with subdiffraction-limited widths for convoluting with objects with arbitrary shapes. Our approach can be viewed as an integral form of the super-resolution quantification widely accepted in fluorescent microscopy. It is shown that the PDMS slabs adhere to the surface of nanoplasmonic structures so that the tips of embedded spheres experience the objects' optical near-fields. The resolution values of $\sim\lambda/6$-$\lambda/7$ are demonstrated for imaging arrays of Au and Al dimers and bowties. It is shown that the PDMS slabs can be translated along the surface of investigated samples after liquid lubrication. Initially, the resolution is diffraction limited; however the super-resolution gradually recovers as the lubricant evaporates. Along with microspheres, we studied imaging through etched microfibers[5] and observed the resolution $\sim\lambda/6$ in the direction perpendicular to the fiber with hundreds of times larger field-of-view in comparison to microspheres. This work opens ways of developing novel optical components for super-resolution imaging of nanoscale structures.



(a) Experimental setup showing a microsphere in air producing a magnified virtual image. (b) Barium-titanate glass (BTG) microspheres embedded in a movable slab controlled by a manipulation probe. (c) Image of BTG microspheres inside a PDMS slab, (d) SEM image of the Au bow-tie, (e) calculated and (f) measured optical image of the bow-tie obtained through embedded BTG microsphere. (g) Image of etched silica microfiber, (h) SEM image of the Au dimers, (i) calculated and (j) measured optical image of the dimers obtained through microfiber.

Acknowledgment

The Lincoln Laboratory portion of this work was sponsored by the Department of the Air Force under Air Force Contract FA8721-05-C-0002. Opinions, interpretations, recommendations and conclusions are those of the authors and are not necessarily endorsed by the United States Government.

References

1. Z. Wang et al., Nat. Commun. **2**, 218 (2011).
2. V. N. Astratov and A. Darafsheh, US patent publication 2014/0355108 A1.
3. K. W. Allen et al., IEEE Proc. of NAECON Conf., Dayton, June 24-27 (2014), pp. 50-52.
4. K. W. Allen et al., Ann. Phys. (Berlin) 527, 513 (2015).
5. K. W. Allen et al., accepted to Opt. Express (2015).